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Model for the Quasifree Polarization-Transfer Measurements in the (p,n) Reaction at 495 MeV

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Abstract

The recent $(\vec{p},\vec{n})$ polarization transfer experiments show the ratio of spin-longitudinal to spin-transverse response functions R_L/R_T, measured at a three-momentum transfer of 1.72 fm^{-1} in ^{12}C and ^{40}Ca, to be essentially unity for small projectile-energy loss. This can be explained theoretically if the nucleon-nucleon tensor interaction is zero at this momentum transfer. We can partially achieve this by introducing a density dependent ρ-meson mass m_ρ^* as well as a nucleon effective mass m_N^*. In addition the pion contribution must further be reduced by softening of the πNN form factor.

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1 Introduction

Recent experiments on the $(\vec{p},\vec{n})$ reaction by McClelland *et al.* [1] have strikingly confirmed earlier indications [2, 3], that the ratio of spin-longitudinal to spin-transverse response functions, R_L/R_T, measured at a three-momentum transfer of 1.72 fm^{-1} in ^{12}C and ^{40}Ca is essentially unity for small projectile-energy losses, decreasing somewhat below unity for energy losses > 70 MeV. These results put in doubt many theoretical predictions that there should be a "softness" in the longitudinal channel due to the pion-exchange tail of the NN interaction. At momentum transfers such as those selected in the experiment this would substantially increase the longitudinal response, R_L, above the transverse one. The experimental findings are consistent, however, with the high-energy Drell-Yan experiments [4] which show no enhancement of the pion cloud in nuclei as compared to that of the free nucleon.

We propose a model, and carry out a schematic calculation, which connects the analysis of the quasifree polarization-transfer measurements with the Drell-Yan experiments [4], and, also, with the measurements of the charge and current response in quasielastic electron scattering [5]. By pushing our assumptions somewhat, possibly to an extreme, we are able to explain the quasifree polarization transfer measurements. After outlining the underlying ideas we give results of a semi-realistic model calculation which bears out most of the features of the schematic treatment.

2 Development

The quasielastic $(\vec{p},\vec{n})$ polarization transfer experiments are interpreted theoretically in terms of a spin-isospin interaction, usually taken to be (Eq. (1) of ref. [1])

$$\begin{aligned} V_{\sigma\tau}(q,\omega) = \left(\frac{f_\pi^2}{m_\pi^2}\right)\bigg\{ & \left(g' + \frac{q^2}{\omega^2-(q^2+m_\pi^2)}\Gamma_\pi^2(q,\omega)\right)\boldsymbol{\sigma}_1\cdot\hat{\mathbf{q}}\boldsymbol{\sigma}_2\cdot\hat{\mathbf{q}} \\ & + \left(g' + C_\rho\frac{q^2}{\omega^2-(q^2+m_\rho^2)}\Gamma_\rho^2(q,\omega)\right)\boldsymbol{\sigma}_1\times\hat{\mathbf{q}}\boldsymbol{\sigma}_2\times\hat{\mathbf{q}}\bigg\}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2. \end{aligned} \tag{1}$$

It includes pion-and rho-meson exchange and accounts for short-range correlations via the parameters g' and C_ρ. The notation suggests that the longitudinal response is determined by pion exchange, except for g', and that the transverse response is governed by ρ-meson exchange. This is misleading. As Baym and Brown [6] made clear, because of short-range correlations, the ρ-meson contributes importantly to g' the longitudinal response is strongly affected. This argument will be essential for our discussion.

When looking at differences in the interaction which could cause a deviation of R_L/R_T from unity, it is more transparent to go back to the decomposition in terms of central and tensor invariants. Ignoring formfactors for the moment one has

$$V_{ten}(q,\omega) = \Big\{ -\Big(\frac{f_\pi^2}{m_\pi^2}\Big)\Big[\frac{\boldsymbol{\sigma}_1\cdot\mathbf{q}\boldsymbol{\sigma}_2\cdot\mathbf{q} - \frac{1}{3}(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)q^2}{(q^2+m_\pi^2)-\omega^2}\Big] + \Big(\frac{f_\rho^2}{m_\rho^2}\Big)\Big[\frac{\boldsymbol{\sigma}_1\cdot\mathbf{q}\boldsymbol{\sigma}_2\cdot\mathbf{q} - \frac{1}{3}(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)q^2}{(q^2+m_\rho^2)-\omega^2}\Big]\Big\}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2. \tag{2}$$

Only this part can cause a difference (see [7] for a review) and another way is interpreting the experiment is to say that the tensor force is not active. For our further discussion we adopt as values of coupling constants

$$f_\rho^2/m_\rho^2 = 2f_\pi^2/m_\pi^2, \tag{3}$$

which is 5 % larger than the central value of the Höhler and Pietarinen analysis [8]. It should be mentioned that the Bonn Potential includes the same π and ρ-exchange components, although f_ρ^2/m_ρ^2 is taken to be $\sim$ 20 % smaller that in (3). The factor of 2 simplifies our model discussions and is certainly within the Höhler and Pietarinen uncertainty. In the context of meson exchange this larger factor, can be justified by the inclusion of the two-pion continuum [9] which we shall make more detailed use of below.

The rough equality for the responses

$$R_L(q,\omega) \cong R_T(q,\omega) \tag{4}$$

for the range $q \sim 1.72 - 1.75$ fm^{-1} and small ω, with R_L decreasing somewhat below R_T for these q and $\omega > 70$MeV, as seems to be required consistently by several experiments [1]-[3], can be accomplished by making $V_{ten}(q,\omega\approx 0)\sim 0$. This implies that

$$\frac{f_\pi^2/m_\pi^2}{f_\rho^2/m_\rho^2}\frac{(q^2+m_\rho^2)}{(q^2+m_\pi^2)} \cong 1. \tag{5}$$

Since $m_\pi^2 \ll q^2 \ll m_\rho^2$, this simplifies to

$$\frac{f_\rho^2/m_\rho^2}{f_\pi^2/m_\pi^2}(1+m_\rho^2/6m_\pi^2)^{-1} \cong 1 \tag{6}$$

for $q \sim 1.72\ \text{fm}^{-1} = 2.4 m_\pi$. Unfortunately for this simple explanation, using m_π and m_ρ from the Particle Data book, this ratio is 0.4 instead of unity.

One might argue that a number of effects have been left out, but we shall show by more detailed calculations later that our simple estimate is quite realistic. In particular, effects of two-body correlations are not large since the tensor interaction chiefly connects two-nucleon states of relative zero angular momentum to $L = 2$ states and the centrifugal barrier in the latter suppresses correlation effects . Note that because of this barrier, effects come chiefly from distances larger than $r \sim \hbar/q$, and the meson-exchange model should be adequate.

Brown and Rho [10] have suggested that meson masses as well as the nucleon effective mass should decrease with increasing density *in medium*. Given that [7]

$$\frac{f_\rho}{m_\rho} = g_{\rho NN} \frac{(1+\kappa_V^\rho)}{2m_N} \tag{7}$$

and, in accordance with [10] not scaling $g_{\rho NN}$, we find that the condition (6) can be satisfied if

$$\frac{m_\rho^2}{m_\rho^{*2}} \frac{m_N^2}{m_N^{*2}} \cong \left(\frac{m_\rho}{m_\rho^*}\right)^4 \frac{g_A}{g_A^*} = 1. \tag{8}$$

In this estimate we included the loop correction to m_N^* found in the Skyrme model and reproduced in Brown and Rho [10]. Loop corrections also enter in $g_{\pi NN}$ from which f_π derives, decreasing $g_{\pi NN}$ slightly with increasing density [13]. But this decrease is small compared with that for g_A and we neglect it.

The pion mass m_π which is generated by explicit chiral symmetry breaking, does not scale as the other masses [10, 11, 12]; to a good approximation it is constant over the range of densities considered here, although from analysis of pionic atoms it is known that the optical potential is slightly repulsive so that the *in medium* pion mass actually increases slightly with density [12]. We neglect the increase in m_π as well as the decrease in $g_{\pi NN}$ [13]. Although both effects decrease the *in medium* pionic enhancement, they are small, at most a few percent.

Taking g_A^* to be $\sim$ unity [14, 15] in nuclei, we find $(m_\rho/m_\rho^*)^4 \cong 2$, giving

$$\frac{m_\rho^*}{m_\rho} = 0.84. \tag{9}$$

In obtaining this answer we have taken what we consider to be the minimum possible g_A^* and a rather large f_ρ^2/m_ρ^2, but our values for both cases have been commonly used in the literature. QCD sum rule calculations [16, 17] produce[2]

$$\frac{m_\rho^*(\rho_0)}{m_\rho} \cong 0.8. \tag{10}$$

which is not so different from our estimate.

3 Numerical Results

For a more quantitative analysis we use a spin-isospin interaction based on the recent work by Hippchen *et al.* [9] which, in addition to the ρ meson, includes effects of the $\pi\pi$ continuum. This interaction (OBEPH) is consistent with "strong ρ" coupling as obtained from the Höhler-Pietarinen analysis . Effects of short-range correlations are included by multiplying $V_{\sigma\tau}$ by a correlation function $f(r) = 1 - j_0(r/r_c)$ with $r_c = 0.19$ fm [9] . This value for r_c has been extracted from a fit to the scattering observables over a wide range of energies. The resulting static spin-longitudinal and spin-transverse interactions are displayed as the dashed lines in Fig. 1. They show the familiar q-dependence. It is instructive the extract the Fermi-Liquid parameter g' and the C_ρ factor from this interaction, which are used in phenomenological parameterizations such as Eq. (1). The particular form used in Eq. 1 is not very suitable , however, since it results in a strong q-dependence of these parameters. A better choice [20] is

$$\begin{aligned} V_{\sigma\tau}(q,\omega) &= \Big(\frac{f_\pi^2}{m_\pi^2}\Big)\Gamma_\pi^2(q,\omega)\Big\{\Big(g' + \frac{q^2}{\omega^2 - (q^2+m_\pi^2)}\Big)\boldsymbol{\sigma}_1\cdot\hat{\mathbf{q}}\boldsymbol{\sigma}_2\cdot\hat{\mathbf{q}} \\ &+\Big(\Gamma_\pi^2(q,\omega)g' + C_\rho\frac{q^2}{\omega^2-(q^2+m_\rho^2)}\Gamma_\rho^2(q,\omega)\Big)\boldsymbol{\sigma}_1\times\hat{\mathbf{q}}\boldsymbol{\sigma}_2\times\hat{\mathbf{q}}\Big\}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2. \end{aligned} \tag{11}$$

Comparing the static limits of the OBEPH potential and $V(q,0)$ makes it possible to extract then g' and C_ρ . The results for g' are given by the dashed lines in the lower part of Fig. 1. The momentum dependence is weak and the values are smaller than those extracted from Gamow-Teller systematics ($g' \sim 0.7 - 0.8$). The parameter $C_\rho = 3.65$ is also found to be weakly q dependent but it is significantly larger than what is typically used for "strong ρ" coupling ($C_\rho \sim 2$), as to be expected from the inclusion of the $\pi\pi$ continuum [9].

[2]Hatsuda and Lee [17] give 0.82 as their central value. Chanfray and Ericson [18] have shown that exchange current type processes involving the virtual pion field decrease the quark condensate further by 10-20 % over that of Hatsuda and Lee. Including this correction will bring $m_\rho^*(\rho_0)/m_\rho$ down to ~ 0.8.

With medium-modified hadron masses the only parameter which enters the spin-isospin interaction is m_ρ^*. This is easily incorporated in the OBEPH potential. One can then treat m_ρ^*/m_ρ as a parameter so as to force the tensor interaction V_{ten} zero at the relevant momentum transfer, as discussed in the previous section. It turns out that the resulting value is close to $m_\rho^*(\rho_0)/m_\rho = 0.8$, constituent with QCD sum rule values and our schematic calculation. The resulting interactions are shown as the full lines in Fig. 1. In both, V_L and V_T, we find a strong increase in the repulsion with g' going from ~ 0.6 to a value near unity (lower part of Fig. 1). At the same time the two interactions become weak and nearly equal near $q_0 = 1.72$ fm^{-1}, the momentum transfer of the experiment. More quantitatively this is illustrated by the nuclear matter response functions and the ratio R_L/R_T, both at ρ_0, which are displayed in Fig. 2. As is well known, without medium modifications, R_L and R_T are quite different (dashed lines in the upper part of Fig. 2) and the ratio is strongly energy dependent (dashed line in lower part). A dropping ρ-meson mass wipes out this effect (full line) as experiment would suggest. At the same time, R_L and R_T are rather close to the free response.

While a nuclear matter calculation with dropping ρ mass can explain the LAMPF measurement one has to bear in mind the surface nature of the (p,n) reaction. Without performing a sophisticated finite-nucleus DWBA calculation [19] we can still get some realistic estimate for the finite nucleus effects by using a semi-classical description of the response functions and treating the spin-isospin interaction in a local density approximation (LDA), *i.e.* including a density dependence for m_ρ^*/m_ρ. Following the work of ref. [20] we obtain the finite-nucleus response functions as

$$R^A_{L,T}(q,\omega) = \int d^3r R^{NM}_{L,T}(q,\omega;\rho(r))F(r) \tag{12}$$

where $R^{NM}_{L,T}(q,\omega,\rho)$ are the *local* nuclear matter response functions, including longitudinal-transverse mixing through the surface (see [20] for details), and $F(r)$ is a weight factor derived from the projectile distortion function. It can be evaluated reliably in the Eikonal approximation. Assuming a linear density dependence for the ρ-meson mass as $m_\rho^*/m_\rho = 1 - c\rho/\rho_0$, as suggested by available QCD sum rule calculations, the results for ^{40}Ca are shown in Fig. 3. The upper part displays R_L and R_T with (full lines) and without (dashed line) dropping mass. As for nuclear matter , their differences are drastically reduced and the response functions are close the free response (dashed-dotted line). In the ratio the effect is not as dramatic, however . Nonetheless, there is a significant improvement for lower energies.

We have also included effects from coupling to isobar-hole excitations which are known to increase the tensor interaction in the nuclear medium. When dropping the ρ-meson mass these effects are negligible, however, because of the smallness of $V_{L,T}$ at $q = 1.72$ fm^{-1}.

4 Discussion

We have investigated a model with dropping hadron masses to explain the equality of the spin-longitudinal and -transverse responses, as inferred from recent quasifree polarization-transfer $(\vec{p},\vec{n})$ measurements at LAMPF. A decrease of the ρ meson mass with density leads to an increase in its tensor interaction which alters the momentum dependence of the longitudinal and transverse interactions. In nuclear matter and semi-classical finite-nucleus calculations, a value of $m_\rho^*/m_\rho = 0.8$ explains the data. Such a value seems low, given the surface nature of the (p,n) reaction. Using a Glauber estimate, we find that the nucleus is probed at $\sim 0.6\ \rho_0$ which yields $\langle m_\rho^*/m_\rho\rangle = 0.88$, when using a linear density dependence. With such a value R_L/R_T is still reduced but not enough to explain the data. A more detailed LDA calculation confirms this accurately. On the other hand, an effective ρ-meson mass of 0.88 fits well with values deduced from other experiments. For instance, in an analysis of (e,e') and (p,p') scattering data at 318 MeV on the stretched $12^-_{1,2}$ and 14^- states in ^{208}Pb [22] agreement between the electron and proton quenching factors can be found for effective masses

$$\langle\frac{m_\rho^*}{m_\rho}\rangle = 0.79 - 0.86. \tag{13}$$

Similarly, from studies of the $(\vec{p},\vec{p}')$ polarization transfer at $E_p = 200$ MeV in ^{16}O, Stephenson and Tostvin [23] find that lowering m_ρ^* to

$$\langle m_\rho^*/m_\rho\rangle = 0.94 \pm 0.2 \tag{14}$$

changes the effective isovector spin interaction so as to significantly improve the fit to the data. In ^{10}B $(\vec{p},\vec{p}')$, at the same energy, Baghaei *et al.* [24] find that decreasing $\langle m_\rho^*/m_\rho\rangle$ to 0.9 substantially improves their fit to the data.

It is clear that lowering $\langle m_\rho^*/m_\rho\rangle$ to the ~ 0.84 of Eq. (9) would improve our fit to the data. Alternatively we can seek to cut down the pion exchange contribution relative to that of the ρ-exchange, chiefly at the relatively large momentum transfer of $q = 1.72$ fm^{-1} of the polarization transfer experiment. This can be achieved by changing the pion form factor $\Gamma_\pi(q, \omega)$. Whereas a monopole form factor with a cut off $\Lambda_\pi = 2$ GeV was used in the OBEPH of Ref. [9] Huang *et al.* [25] find that Λ_π should be lowered to ~ 950 MeV in order to fit the sea quark distribution in deep inelastic lepton scattering from hadrons (others [26, 27] have argued for an even lower value). More recently a microscopic model using a $\pi\rho$ vertex and including rescattering contributions has confirmed these findings [28]. Such a low form factor, of course, cannot describe the deuteron properties. To reconcile this difficulty Holinde and Thomas have introduced a heavy point-like "pion" (the π') of mass 1.3 GeV [29]. By adjusting the $\pi' NN$ coupling constant good fits to the phase shifts and the deuteron properties could be obtained. This picture, in conjunction with the $\pi\rho$ vertex model [28], then allows to study medium modifications of the πNN form factor. Such modifications are again produced by a dropping ρ mass. Preliminary calculations [30] indicate a significant softening, chiefly from the rescattering term. The "effective" πNN cut off in the OBEPH potential drops from 2 GeV to about 1 GeV. Changing Λ_π to 1 GeV leads to the dashed-dotted curve in Fig. 3, which is quite close to the data.

We conclude that inclusion of the *medium dependence of the ρ-meson mass and of the nucleon effective mass* significantly reduces the isovector part of the tensor interaction and removes much of the discrepancy between the ratio of spin-longitudinal and spin-transverse response functions. Agreement with experiment further improves by a softening of pion-exchange form factor. In microscopic models of the πNN vertex such a softening is caused by the same physical mechanism. Our fits deteriorate for higher values of ω, however, and new physics, which we have not considered, may enter there.

The medium dependence of the ρ mass leads to a very different momentum dependence of the spin-isospin interaction as that in free space (see Fig. 1). This implies a different q-dependence of the ratio R_L/R_T. Our predictions are given in Fig. 4. At q=1.1 fm^{-1}, currently measured at LAMPF [31], one should observe a significant enhancement at low ω (dashed line) while at q-tranfers > 2 fm^{-1} the ratio should be strongly suppressed since V_T becomes attractive (dashed-dotted line). We therefore consider measurements at different q-tranfers crucial to our model.

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Figure Captions

Fig. 1: upper part: the spin-longitudinal and spin-transverse free OBEPH interactions (dashed lines) and the medium-modified interactions for $m_\rho^*/m_\rho = 0.8$ (full lines). lower part: the Fermi-liquid parameter $g'(q)$ in free space (dashed line) and in medium (full line).

Fig. 2: upper part: the nuclear matter spin-longitudinal and spin-transverse response functions as a function of energy ω and at fixed momentum transfer $q_0 = 1.72$ fm^{-1}. The dashed lines use the free OBEPH interaction while the full lines result from dropping the ρ-meson mass. The dashed-dotted line denotes the free Fermi gas response. lower part: the ratio R_L/R_T from the OBEPH interaction (dashed) and with dropping mass (full). The data were taken from ref. [1].

Fig. 3: same as Fig. 2 but for ^{40}Ca. The dashed-dotted line gives results for a cut off $\Lambda_\pi = 1$ GeV.

Fig. 4: the ratio R_L/R_T for several momentum transfers as predicted by our model. A "soft" cut off $\Lambda_\pi = 1$ GeV has been used.